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# Recent National Transonic Facility Test Process Improvements (Invited)

W. A. Kilgore, S. Balakrishna, C. W. Bobbitt, Jr.
and J. B. Adcock
NASA Langley Research Center
Hampton, Virginia

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# RECENT NATIONAL TRANSONIC FACILITY TEST PROCESS IMPROVEMENTS

W. A. Kilgore*, S. Balakrishna*, C. W. Bobbitt, Jr.†, and J. B. Adcock‡
Aerodynamics, Aerothermodynamics, and Acoustics Competency
NASA Langley Research Center
Hampton, Virginia

## ABSTRACT

This paper describes the results of two recent process improvements; drag feed-forward Mach number control and simultaneous force/moment and pressure testing, at the National Transonic Facility. These improvements have reduced the duration and cost of testing. The drag feed-forward Mach number control reduces the Mach number settling time by using measured model drag in the Mach number control algorithm. Simultaneous force/moment and pressure testing allows simultaneous collection of force/moment and pressure data without sacrificing data quality thereby reducing the overall testing time. Both improvements can be implemented at any wind tunnel. Additionally the NTF is working to develop and implement continuous pitch as a testing option as an additional method to reduce costs and maintain data quality.

## INTRODUCTION

The U.S. National Transonic Facility (NTF) was the first large closed circuit fan drive cryogenic pressure tunnel designed to provide flight Reynolds number testing at transonic speeds in a ground based facility. Several problems have plagued the NTF since it became operational in 1984 and have limited its ability to consistently provide cost effective high quality data at flight Reynolds numbers. Many of these problems have been solved over the years as lessons about large cryogenic tunnel operations and high Reynolds number testing techniques matured. Improvements to the tunnel performance capabilities, reliability and data quality have also been implemented over the years. Still, despite its extensive Reynolds numbers testing capability as shown in figure 1, testing at the NTF is limited due to its expense when compared with conventional tunnels.

Recently, several studies have been conducted to investigate reducing the cost of testing at the NTF through process improvements. The most recent efforts (FY-2000) were focused on the implementation of drag feed-forward Mach number control and simultaneous force/moment and pressure testing. Both of these improvements reduce the cost of testing at the NTF by reducing the test duration.

## NOMENCLATURE

| | |
|---|---|
| $A$ | area of duct |
| AWG | American Wire Gauge |
| afwa | axial force, wind axis (i.e. drag) |
| ESP | electronic scanning pressure |
| FRS | Flow Reference System |
| igv | inlet guide vane |
| $k_1$ | circuit loss factor |
| $N$ | fan speed |
| $M$ | Mach number |
| $P_{inlet}$ | fan inlet pressure |
| $P_S$ | tunnel static pressure |
| $P_T$ | tunnel total pressure |
| $\Delta P$ | pressure loss |
| $q$ | dynamic pressure |
| RCS | Research Computer System |
| Re | Reynolds number in million/chord |
| $t$ | time |
| $T$ | tunnel flow total temperature |
| $u$ | velocity |
| $x$ | axial direction, tunnel flow axis |
| $\alpha$ | angle of attack, AoA |
| $\beta$ | side slip angle |
| $\dot{m}$ | test section mass flow |
| $\delta_{igv}$ | change in inlet guide vane angle |
| $\delta_{rpm}$ | change in fan speed |

* Dynamics and Controls Engineer, Research Facilities Branch, Senior Member, AIAA
* Senior Research Scientist, ViGYAN Inc.
† Test Engineer, Research Facilities Branch,
‡ Consultant, ViGYAN Inc.

## DRAG FEED-FORWARD MACH NUMBER CONTROL

It is well known that in all closed circuit wind tunnels a change in blockage, often related to a change in model angle-of-attack ($\alpha$), causes a change in the test section flow momentum and velocity and hence results in a disturbance to the test section Mach number. Adjustments are made to the fan pressure ratio via the Mach number controller to recover and maintain the test section Mach number at the NTF. This recovery time is of the order of 7-10 seconds with the optimally tuned Mach number controller. The recovery response is related to Mach number measurement/process settling delays.

The NTF uses a combination of fan speed ($N+\delta_{rpm}$) and fan inlet guide vane angle ($igv+\delta_{igv}$) to achieve the required fan pressure ratio.[1] This relationship can be modeled as:

$$\frac{\sum_{circuit} \Delta P}{P_{inlet}} = f(N+\delta_{rpm}, igv+\delta_{igv})$$

During the standard process for an angle-of-attack sweep, N is held constant ($\delta_{rpm}=0$) and $\delta_{igv}$ is adjusted to account for changes in the circuit pressure losses. Therefore, to improve the response of the Mach control, a faster system is needed to sense the change in momentum in the test section, and to translate this change into the required adjustment in $\delta_{igv}$.

The momentum change in the test section can be represented by the momentum equation of duct flow:

$$A\frac{\partial P}{\partial x} = \frac{\partial(\dot{m})}{\partial t} - \frac{\partial(\dot{m}u)}{\partial x} - k_1 \dot{m}u$$

Where $k_1 = f(\alpha, \beta, M, Re)$ represents the momentum loss coefficient due to blockage and other test section losses. By Newton's principles, this loss in momentum can be represented as a force (in this application, the axial force in the wind axis (*afwa*); i.e. drag). This force measurement, made using the model force-balance, responds more rapidly than the Mach number measurement system. Therefore this measured drag force can be used for feed-forward to Mach controller, thereby realizing faster Mach number recovery times.

To implement this process, a relationship between the fan pressure control and *afwa* must be determined. For the NTF, this relationship is between the drag force (*afwa*) and the $\delta_{igv}$ at a constant fan speed. Figure 2 shows this relationship for a range of tunnel conditions.

The slope $\delta_{igv}/afwa$ has been analyzed over a wide range of Mach numbers, Reynolds numbers and tunnel temperatures, and a linear relation has been established between *afwa* and $\delta_{igv}$. This relation is represented as:

$$\delta_{igv} = \frac{0.02}{\sqrt{Re_{million}}}\sqrt{\frac{T}{580}}\,(afwa)$$

Figure 3 shows a detailed graph of how well this linear relation agrees with actual test data from two different transport model tests, as compared to a least-squares fit of the data.

This relation between *afwa* and $\delta_{igv}$ is unique and therefore easily implemented as the drag feed-forward component in the Mach number controller. Figure 4 shows the schematic of NTF Mach number control loop using this drag feed-forward approach.

The Mach number control process is as follows: First, the test-section Mach number is calculated.[2] This Mach number is compared with the Mach number set point to determine a Mach number error. The Mach number error is passed through a nonlinear gain schedule Proportional Integral (PI) controller to determine the inlet guide vane angle.[1]

The implementation of drag feed-forward required only minor software code changes that introduce a second summation where the *afwa* applies a small limited inlet guide vane angle bias to the igv signal. This igv signal is then normalized with the tunnel temperature and outputs the desired inlet guide vane angle.

The results of drag feed-forward Mach number control are shown in Figure 5 for two identical angle of attack changes (0° to -4°) of the same model at identical test conditions. The plot on the left represents drag feed-forward "OFF" and the plot on the right represents drag feed-forward "ON". Comparing these two plots shows that the Mach number settles 4 seconds faster using drag feed-forward. Additionally, the disturbance to the Mach number appears significantly less demonstrating that drag feed-forward also maintains a tighter Mach number control during model attitude changes. This offers a significant benefit in improved Mach number stability when performing continuous pitch testing and reducing unsteady loads on the model.

Summary

The use of a drag feed-forward Mach number controller at the NTF has resulted in a faster recovery time for Mach number disturbances caused by angle-of-attack variations. The actual savings from utilizing the drag feed-forward Mach number controller can only be estimated, as is will vary for each tunnel condition and the step size (or change) in angle of attack. For typical high Reynolds number (Re=40million), transonic (M=0.88) test conditions with a 15-point polar, the estimated time saving is about 30 seconds. This corresponds to significant savings in LN2 cost alone (~$1000 per polar).

This new drag feed-forward Mach number controller responds immediately to blockage changes caused by angle-of-attack changes instead of waiting for the response of the Mach number measurement system. The control law is simple and robust and the concept can be used in any closed circuit subsonic tunnel with Mach number capability via fan pressure ratio.

## SIMULTANEOUS FORCE AND PRESSURE

In the past it has been common practice at the NTF to divide a test program into two parts. The first part included the simultaneous measurement of the balance forces/moments along with model wing pressures and was followed by the second part that included only balance forces/moments. It was a concern that the configuration in the first part compromised the balance force/moment data because of the large number of pneumatic tubes and instrumentation wiring bridging the metric and non-metric portions of the balance. Therefore, tubing and wiring would be removed from the model and a reduced test matrix repeated as the second part of the test program to obtain the highest possible quality force and moment data. This typically adds 25% to the duration of a test and also increased total test cost.

Several facilities throughout the world have been successful in developing approaches and methodologies that ensure high quality force/moment data whilst simultaneously making model pressure measurements. Because of this tremendous potential cost savings the NTF also undertook the development of a simultaneous force/moment and pressure measurement process. The approach at the NTF similar to other facilities is to minimize the load carrying capability of tubes or wires that bridge the balance and to provide a simple method to verify that the force/moment data is not being affected.

Tubes and Wires

In a typical test at the NTF there are several pneumatic tubes and electrical wires that support the Electronic Scanning Pressures (ESP) and Angle of Attack (AoA) systems, which cross the metric break of the force and moment balance. The ESP system requires wiring for the data signals, environmental heaters, and temperature measurements along with several pneumatic tubes. The AoA system also requires wires for the data signals, environmental heaters and temperature measurements.

To support this effort, the following changes were made to the instrumentation tubing and wiring used in the model. The existing nylon pneumatic tubing was replaced with identical size (OD=0.060in) Teflon tubing, which is more flexible and provides reduced friction. Teflon coated 24AWG and 26AWG wire (dia.≈0.038in and dia.≈0.032in) was replaced with smaller, more flexible 34AWG Teflon coated wire (dia.≈0.0210in), requiring more wires but providing more flexibility. The 34AWG wire tensile strength is about 85% of the 26AWG wire. Additionally, the type T thermocouples (solid 24AWG) used for temperature measurements in the ESP system were replaced with RTDs, which increased the actual number of wires for temperature measurements but permitted the use of 34AWG wire.

Table 1 provides the tubing and wiring requirements to each instrumentation system before and after the process improvement. It should be noted that the actual number of wires bridging the balance increased from 58 to 115 requiring an increase in the model build up time to ensure proper configuration and quality are maintained (34AWG is very fragile and difficult to work with).

With these changes in place the next effort concentrated on crossing the balance and maintaining sufficient slack to avoid any loading between the metric and non-metric ends. This was accomplished by avoiding bundling of the wire and tubes together. Wires and tubes were splayed and allowed to move freely in the longitudinal direction. Additionally, because the NTF operates over a wide temperature range (120°F to –250°F) sufficient slack was provided to allow for thermal contraction. These changes are shown in figures 6 and 7.

Verification Method

A key to the successful implementation of simultaneous force/moment and pressure testing is an easily performed and comprehensive verification method. At the NTF this requires a verification method that can be performed with the model at both ambient and cryogenic conditions.

The verification method used at the NTF is to graphically monitor the "balance residuals" during a wind-off angle of attack sweep of the model. The "balance residuals" are defined as the offset in balance loads that remain after the weight tare, wind-off-zero, balance interactions and temperature corrections are applied.[2] In an ideal case the balance residuals should be zero at all model angles during wind-off conditions. If the wind-off balance residuals are not zero, then either the corrections have been misapplied or the balance is being fouled.

Figure 8 shows the plot of Balance Residuals vs. Alpha used for the verification process. The x-axis for each plot is the model angle of attack ($\alpha$) and the y-axes are the respective units for each balance component (lbs, or in-lbs).

In preparation for this verification process, several events must occur to ensure accurate and proper interpretation of the results. First, an accurate weight tare must be obtained. The accuracy of weight tare is a prime factor in the magnitude of the residual. Second, a wind-off-zero (WOZ) must be taken with the model in the current position (upright or inverted) for the angle of attack sweep. It is extremely important to have a good WOZ (true $\alpha$=0 and $\beta$=0).

Once these events are completed, the model is moved at a constant pitch rate over the full range of test angles. This verification process is used for both an upright and an inverted angle-of-attack sweep. As the data is collected, the data trends on the "balance residuals" display are monitored. Ideally, when the model is moving all the data should have a small, constant, and symmetric offset from the zero load line for all model angles.

Offsets other than the ideal as presented in figure 9 must be further examined. This figure shows an offset with a constant slope that is indicative of inaccurate weight tare or weight tare correction. Also shown is an offset that is not centered about zero that indicates a poor WOZ. Sudden jumps or hysteresis are indicative of cables/tubes/seals hanging or sticking and releasing.

The axial component offset is highly dependent on the angle of attack rate sweep as shown in figure 9. This is attributable to lags between AoA and balance gage signal processing and to inertial loads.

This process is repeated at every phase of the model build up to ensure the tubes and wires do not load the balance. If a problem is indicated the tube and wire layout is modified and the entire process is repeated. When the model is installed in the tunnel, and throughout the test, (air and $GN_2$ operations) the process is repeated to ensure data quality is maintained.

Summary

The approach and methodologies presented for using simultaneous force/moment and pressure measurements result in significant savings (25% time reduction and cost savings) for a test program without compromising data quality. The process implemented at the NTF has shown the ability to obtain high-quality force/moment data while simultaneously making model pressure measurements. Additional benefit is obtained from tracking balance residuals since it provides insight to the quality of a weight tare, wind-off zero and applied balance corrections.

## FUTURE IMPROVEMENTS

Continuous Pitch

For the continuous pitch test technique, data are obtained continuously over a specified angle-of-attack range at given test conditions. There are several possible benefits to this approach, including a reduction in test time as compared to pitch-pause testing, and smoother testing through pitch buffet.

To implement this technique at the NTF first required the implementation of drag feed-forward. Changes were then required to the model control and data systems. Once these modifications were made, an initial checkout of the system was performed. Figure 10 shows the pitching moment, axial force, and normal force data for two different pitch rates, as compared to traditional pitch-pause data.

The results presented in figure 10 show that the pitch pause polar takes 260s as compared to 40s for a continuous pitch polar at 0.25°/s. This savings corresponds to a potential 80% cost savings for a test. The continuous pitch polar at 0.25°/s also obtained higher $\alpha$ through pitch buffet.

Initial results are promising, but more work needs to be done to make this a standard test-technique, including addressing the current time lag in the angle-of-attack measurement system, pressure measurement systems and addressing data quality issues.

## CONCLUSIONS

The NTF is working to reduce the cost of testing through several process improvements while still maintaining data quality. The implementation of drag feed-forward Mach number control and simultaneous force and pressure testing are two cost reduction examples presented in this paper that can also be applied to other tunnels.

The NTF continues to develop continuous pitch as a testing option as an additional method to reduce costs and maintain data quality. The combined use of continuous pitch and drag feed-forward will also improve testing techniques near the stall buffet boundary that may allow for testing safely through buffet.

## REFERENCES


1. Balakrishna, S.; Kilgore, W. Allen; and Thibodeaux, J. J.: Control of Large Cryogenic Tunnels, AIAA 92-3930, 17th Aerospace Ground Testing Conference, July 6-8, 1992, Nashville. TN
2. Foster, J. M.; and Adcock, J. B.: User's Guide for the National Transonic Facility Research Data System, NASA Technical Memorandum 110242, April 1996


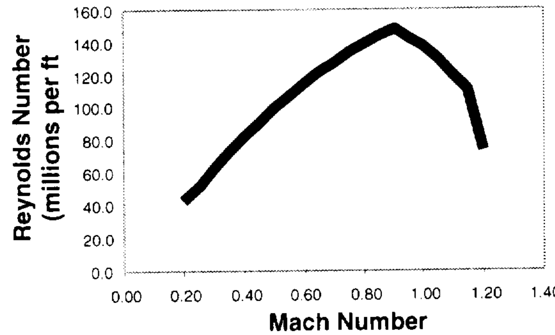


**Figure 1 – NTF Operational Envelope**

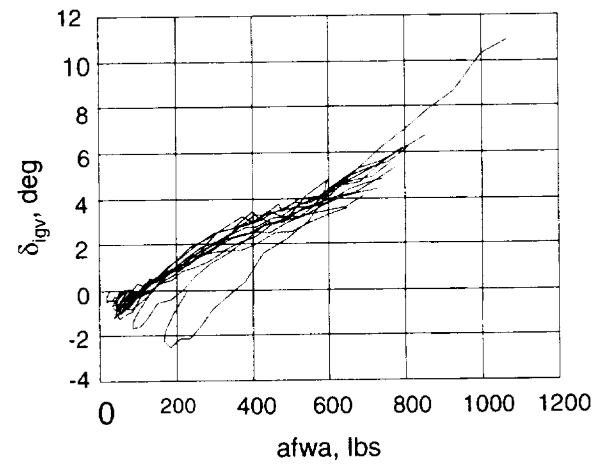


**Figure 2 – *afwa* vs inlet guide vane angle**

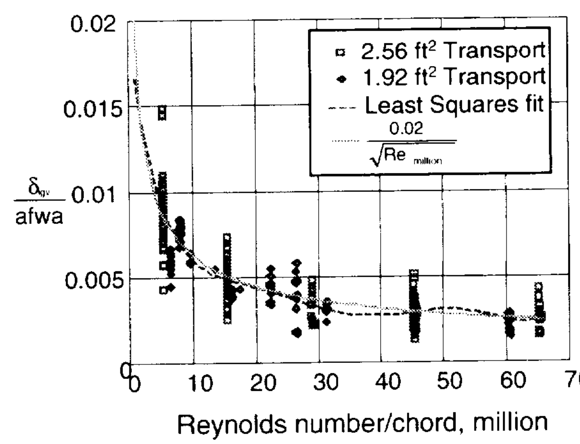


**Figure 3 – Reynolds No. vs $\delta_{igv}$/afwa**

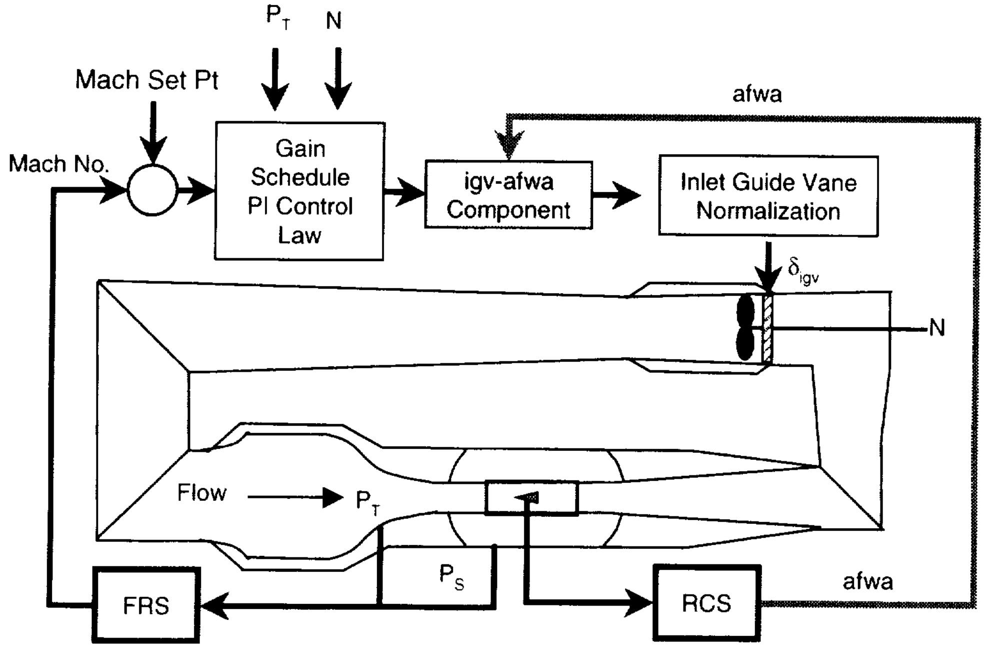


**Figure 4 – Schematic of Mach No. Controller**

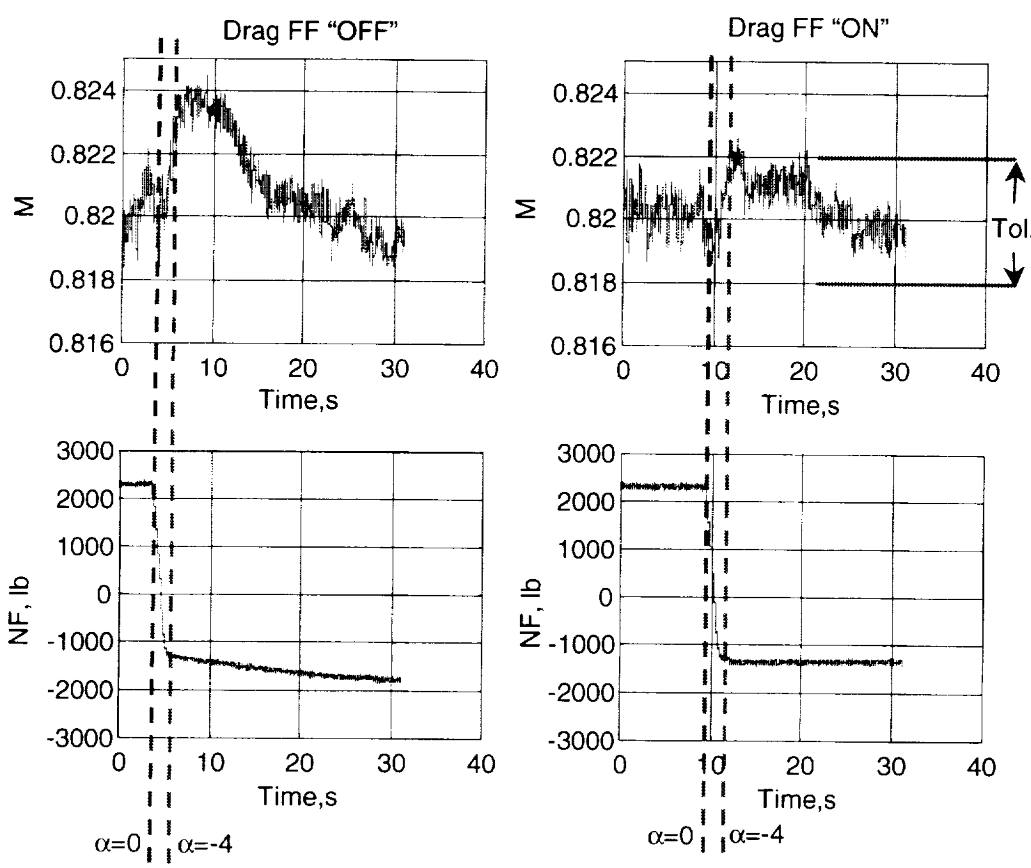


**Figure 5 – Mach No. Performance with Drag Feed-forward**

| | Before | | After | |
|---|---|---|---|---|
| | Number | Size | Number | Size |
| ESP Data Signals | 30 | 26/24 AWG | 57 | 34 AWG |
| ESP Heaters | 5 | 24 AWG | 19 | 34 AWG |
| ESP Temperatures | 8 T/Cs (2 wires each) | 24 AWG (solid) | 5 RTDs (4 wires each) | 34 AWG |
| Pneumatic Tubes | 6 | 0.060" Nylon | 6 | 0.060" Teflon |
| AoA Data Signals | 12 | 26 AWG | 12 | 34 AWG |
| AoA Heaters | 2 | 24 AWG | 4 | 34 AWG |
| AoA Temperatures | 1 RTD (3 wire) | 24 AWG | 1 RTD (3 wires) | 34 AWG |

**Table 1 – Before and After Changes to Wires and Tubes**

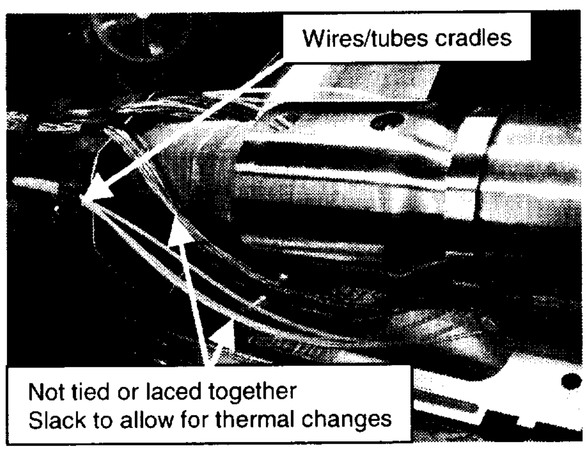


**Figure 6 – Instrumentation in balance adaptor area**

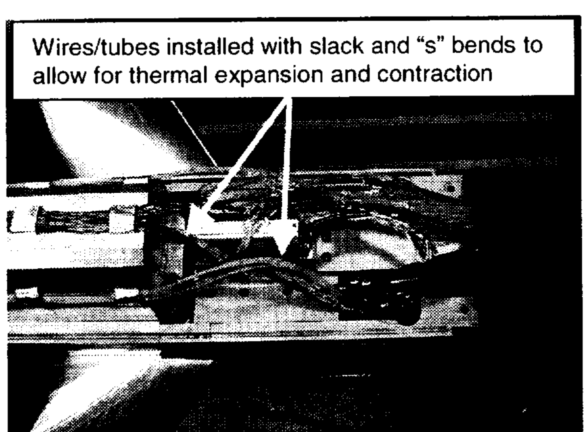


**Figure 7 – Model cavity area for ESP and AoA System**

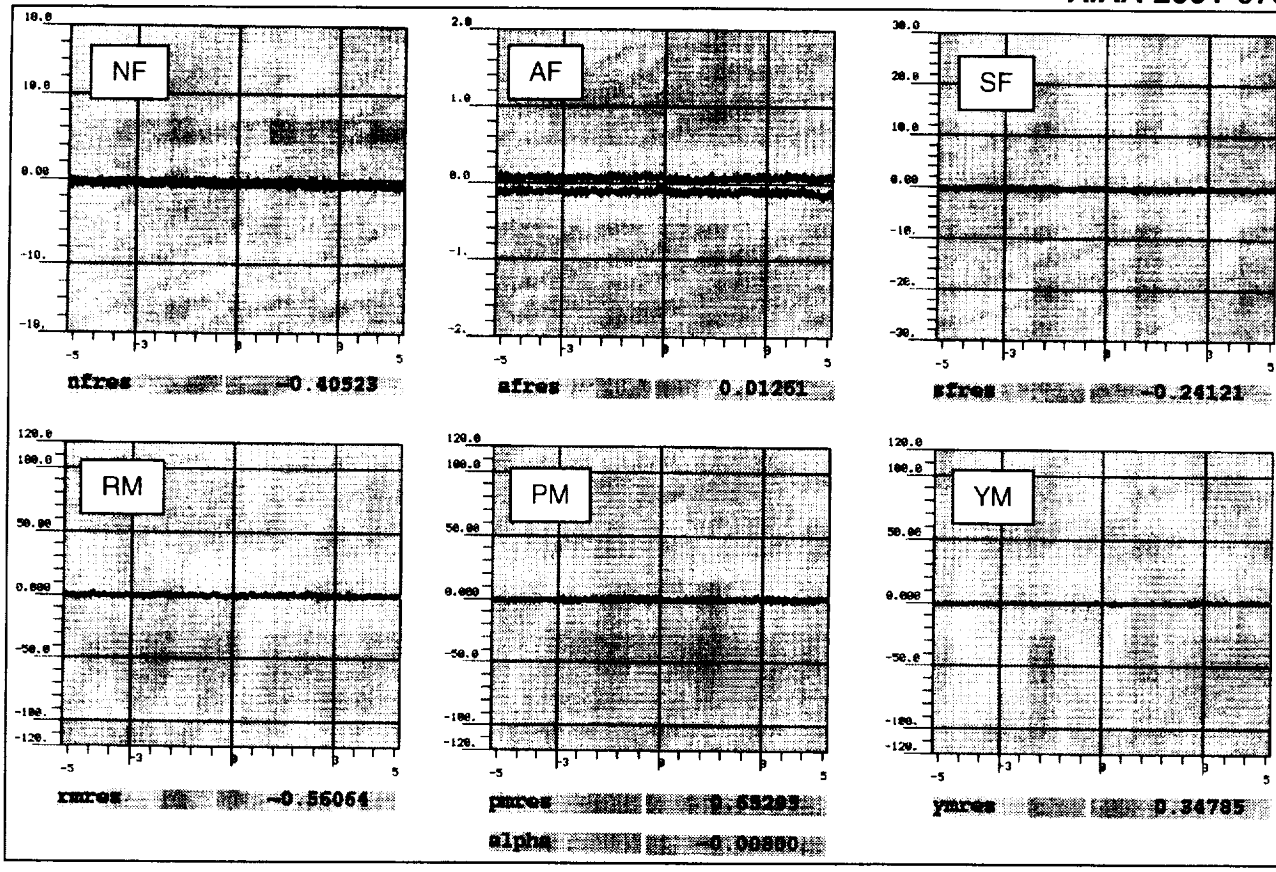


Figure 8 – Balance Residuals vs Alpha

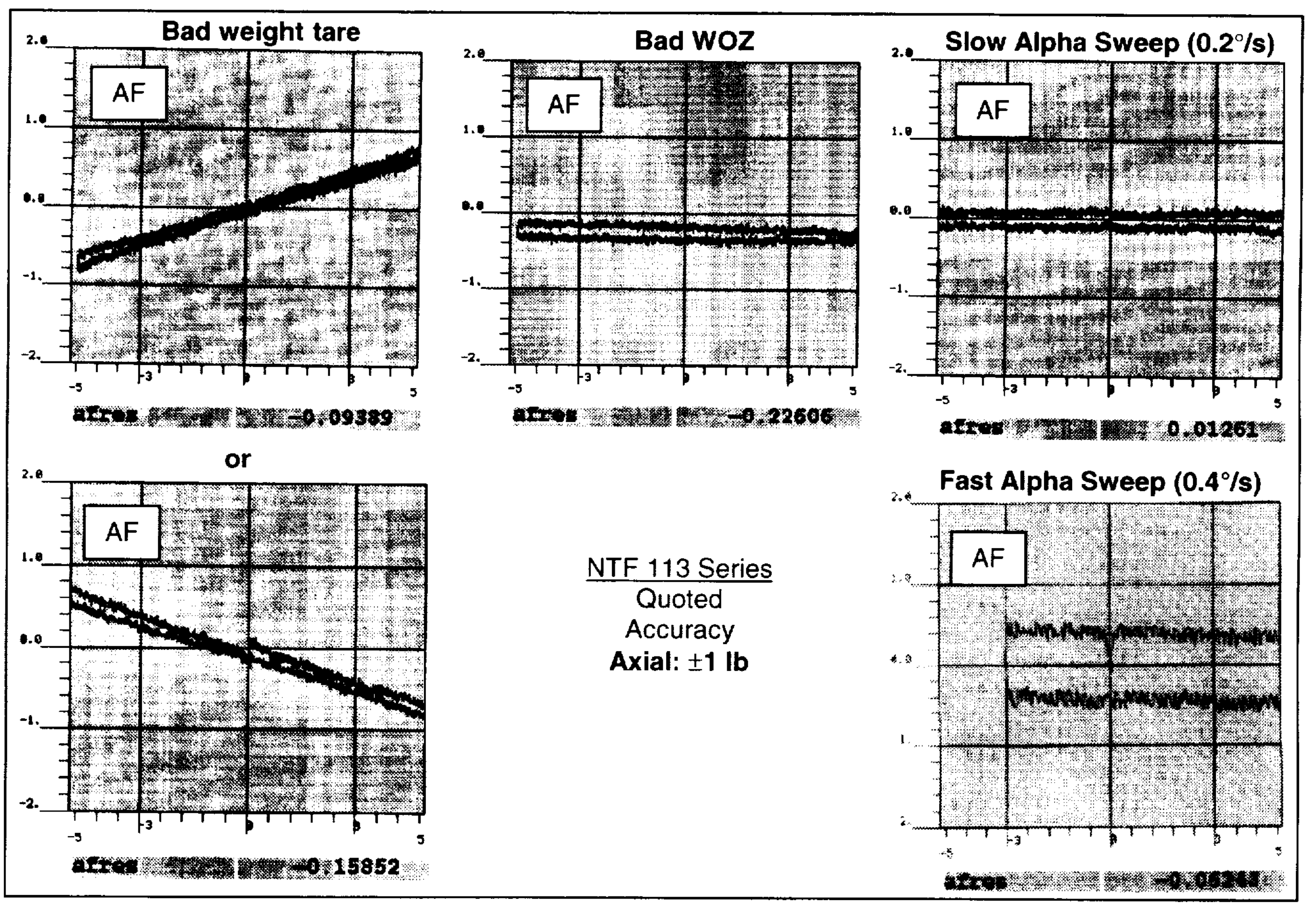


Figure 9 – Balance Residual vs Alpha for Axial

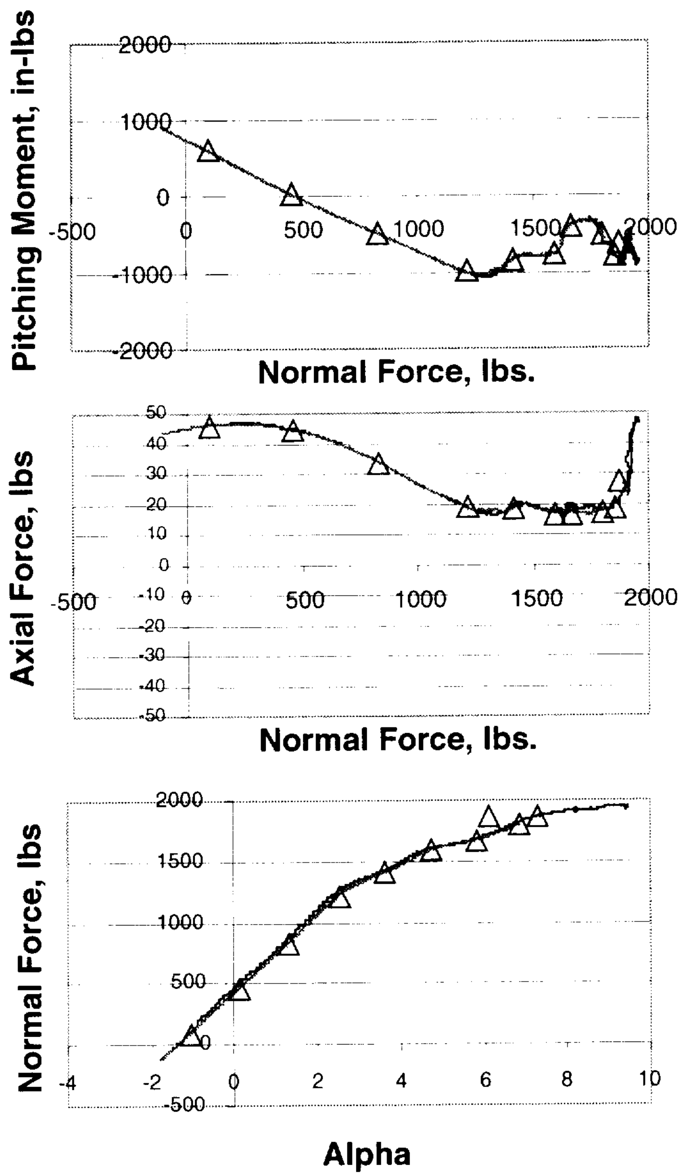


Figure 10 – Preliminary Continuous Sweep Data

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## NASA STI Acquisitions DAA Authorization

The following papers (copies enclosed) have been DAA approved as Unclassified, Publicly Available documents:

**Meeting Presentations:**

39th AIAA Aerospace Sciences Meeting & Exhibit, 1/8-11/2001, Reno, NV:

F. A. Greene, *et al.*: Measured and Computed Hypersonic Aerodynamic/Aeroheating...
T. Liu, *et al.*: Estimating Bias Error Distributions.
E. A. Morelli, *et al.*: Response Surface Modeling Using Multivariate Orthogonal...
C. Bobbitt, Jr., *et al.*: Status of the National Transonic Facility Characterization.
T. Jones, *et al.*: Comparison of Angle of Attack Measurements for Wind Tunnel...
J. N. Moss: DSMC Computations for Regions of Shock/Shock and Shock/Boundary...
W. A. Kilgore, *et al.*: Recent National Transonic Facility Test Process Improvements.
C. L. Rumsey, *et al.*: Isolating Curvature Effects in Computing Wall-Bounded Turbulent...
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Susan H. Stewart

Susan H. Stewart
DAA Representative
NASA Langley Research Center
Mail Stop 196
Hampton, VA 23681-2199

s.h.stewart@larc.nasa.gov
phone: (757) 864-2518
fax: (757) 864-2375